Science of the Total Environment 838 (2022) 156546

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Mixed methods study design, pre-analysis plan, process evaluation and baseline results of trailbridges in rural Rwanda

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HIGHLIGHTS

- Isolation is an impediment to rural development and poverty eradication in Rwanda.
- A mixed methods experimental and observational study will establish casual outcomes.
- Randomized controlled trial for economic outcomes
- Sub-studies for determinants of use and market activity

GRAPHICAL ABSTRACT

ARTICLE INFO

Editor: Jay Gan

Keywords:
Trailbridge
Isolation
Extreme weather event
Impact evaluation
Mixed methods
Remote sensing
Rwanda

ABSTRACT

We present a study design, pre-analysis plan, process evaluation and baseline results designed to establish the impact of trailbridges on health, education, agricultural and economic outcomes of households in rural Rwanda. This intervention and study is being implemented in communities that face barriers to socioeconomic development through periodic isolation caused by flooding. We describe a mixed methods approach to measure the impacts of these trailbridges on outcomes at the village level. The study is anchored on a stepped-wedge randomized controlled trial (RCT) implemented in 147 sites: 97 phased-in intervention sites and 50 long-term control sites. These sites are being monitored in four annual waves comprising of a baseline period and three subsequent follow-up waves. We will supplement the RCT with three sub-studies. First, we are investigating the role of weather events and streamflow variability on temporal and spatial bridge use patterns among intervention sites. We will then find the relationship between the weather events, streamflow and bridge use from motion-activated cameras installed in intervention sites. Secondly, we are following 42 markets serving study sites to investigate the impact of the trailbridges on the market prices of key goods including crops, livestock and agricultural inputs. Lastly, we are following 30 villages that are more distant from the river crossings to determine the spatial extent of the trailbridge impacts. Our study will advance knowledge by generating new data on the impact of rural infrastructure and providing the opportunity to explore a range of outcomes for future evaluation of infrastructure in low- and middle-income countries. We will enable an outcomes-based funding model that ties implementer payments to demonstrated positive impacts of these trailbridges.

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http://dx.doi.org/10.1016/j.scitotenv.2022.156546
Received 9 March 2022; Received in revised form 31 May 2022; Accepted 3 June 2022
Available online 10 June 2022

Furthermore, we will identify cost-effective, easily assessed measures that are highly correlated to the economic and health benefits of the intervention. These measures may then be used by a portfolio of interventions across multiple geographies without always requiring complex trials.

1. Introduction

1.1. Transportation access and rural poverty

Research has established a correlation between isolation and poverty (Bird, 2010). Villages that are physically isolated from social, financial and other forms of capital face an elevated level of underdevelopment and poverty (Weiss et al., 2018). Physical isolation can result from marginalization and natural factors such as topography (Bird, 2010). Flooding and high river flows can exacerbate isolation. Flooded rivers create physical barriers for communities that lack safe water crossing infrastructure. These barriers prevent access to essential services and can lead to labor income losses (Brooks and Donovan, 2020) and loss of human lives in periods of extreme flood events. Similarly, this type of isolation has the potential to reduce school participation for children and can increase transportation costs (Bird, 2010).

Flood extremes associated with rainfall variability have increased in frequency and severity in East Africa. This trend is projected to continue in a warming climate (Wainwright et al., 2020; Shongwe et al., 2011; Otto et al., 2015; Ogega et al., 2020; Ongoma et al., 2018), leading to a rise in impacts partly due to high human population growth in the region (Chen et al., 2020). Besides, it is expected that the increased flood frequency will also lead to a rise in livelihood losses that will affect millions of poor and vulnerable people in the region (Conway et al., 2005). These losses have varying costs on affected populations, and at worst, they can exacerbate poverty among vulnerable households in a community.

To mitigate rural isolation and strengthen resilience for communities and their livelihoods, adaptation interventions need to provide solutions that can guarantee sustained outcomes for long-term community wellbeing. Structurally resilient, safe and cost-effective trailbridges have emerged as a “first-mile” transport infrastructure solution that can help solve the rural isolation challenge (Brooks and Donovan, 2020; Thomas et al., 2021) and contributes to the Sustainable Development Goals (SDG 9) by reducing disparities in accessibility (Weiss et al., 2018). The presence of such infrastructure provides uninterrupted access to services, reduces flood risks during the rainy season and builds resiliency against unpredictable weather. Trailbridges impact the day-to-day life of individuals in isolated rural villages directly through a number of mechanisms (Starkey, 2002). The most direct mechanism is the reduction in time required to get to school, markets, or labor sources (Thomas et al., 2020). Other mechanisms include improved access to social capital available in other communities such as domestic water supply. Trailbridges can also have positive effects on the ability of residents to care for their families and earn stable incomes (Brooks and Donovan, 2020).

Trailbridges are some of the most common rural transportation infrastructure in rural communities in Sub-Saharan Africa (SSA) (Shirley et al., 2021). Although a key connectivity network, most of these bridges are temporary and unsafe due to their poor designs. During high river flows, some of these bridges are washed away by flood waters, thus eliminating the service they provide and exposing people to losses and death. Several development programs have introduced more resilient structural designs and constructed hundreds of these bridges in developing countries. One of those programs is implemented by Bridges to Prosperity (B2P), a nonprofit organization that provides safe access to rural communities globally through the construction of trailbridges. The B2P bridges have since connected more than one million people in 20 countries to critical services (Brooks and Donovan, 2020; Thomas et al., 2021; Shirley et al., 2021).

1.2. Evidence for adaptation policy and interventions

A key requirement by policy makers and funding agencies is reliable evidence to justify continued investments in adaptation interventions (Kaiser and Barstow, 2022). Rural transportation development funding in SSA tends to focus on building rural roads, with little attention on transport systems that can spur farm and village level movements (Hine, 2014). Trailbridges provide this connectivity and improve movement at the village level, with benefits that improve household and community wellbeing. One way to evaluate the impacts of such interventions on target beneficiaries is through impact evaluation studies. A recent one-year, 12-bridge and 12-comparison site impact evaluation was conducted in Rwanda (Thomas et al., 2021). This evaluation revealed an increase in labor market income by 25 % following the establishment of the trailbridges. Additional evidence was provided by Brooks and Donovan (2020) following an impact evaluation conducted in Nicaragua. There was a 75 % increase in farm profits, as well as an increase in labor market income (36 %) and women's participation in the labor force (60 %) following the construction of trailbridges in the country. The study also found that seasonal flash floods in Nicaragua resulted in uncertain access to labor markets and reduced agricultural productivity. Specifically, floods, which prevent access to higher-pay day labourer jobs in nearby towns when a village does not have a trailbridge, induced 18 % lower wage earnings.

Evidence generation through impact evaluations is popular in medical fields, relying heavily on quantitative approaches built around experimental designs such as Randomized Control Trials (RCTs). These methods have then been adapted for other fields including Water Sanitation and Hygiene (WASH) (Thomas et al., 2021; Iribagiza et al., 2021; Nagel et al., 2016), agriculture (Dhehibi et al., 2018), and labor and market sectors (Brooks and Donovan, 2020; Bouguen et al., 2019). RCTs provide strong statistical support but are often costly, time consuming and lack external validity (Victora et al., 2004). These limitations can impede evidence generation in developing economies that lack sufficient budgets to implement such evaluations, but alternative methods that are cost-effective and provide evidence that is equally reliable are becoming available (Brenner et al., 2014). Mixed methods approaches combine experimental and non-experimental approaches and are more suited for many contexts where RCTs are not feasible. Broadly speaking, the choice of an appropriate approach should lead to reliable and credible conclusions. Experts in impact evaluations such as Bamberger and White (2007) argue that a quality impact evaluation must, (i) have a theory of change or a logical framework (*i.e.* define and measure inputs, processes, outputs, intended outcomes and impacts), (ii) develop a counterfactual, (iii) determine the contribution of an intervention to the target beneficiary, (iv) identify factors influencing the magnitude and distribution of the impacts, and (v) provide information about the sustainability of interventions and their impacts. The choice of methods and designs, therefore, should generally be guided by the available resources, the existing constraints, and the nature of the evaluation (Rogers et al., 2015).

Our study is based on this understanding, and we specifically use mixed methods approaches to investigate their applicability in rural Rwanda for the current intervention and to inform future impact evaluations. This work will be an example to improve adaptation policy and interventions in developing economies.

1.3. The Rwanda trailbridge scale up program

1.3.1. Needs assessments

B2P specializes in the development and implementation of rural trailbridge programs that closely engage national and local government entities, and account for all phases of a project life cycle, from site identification to long-term maintenance and asset management. B2P began working with national and district government partners in Rwanda to build trailbridges in 2012, and they launched a joint scaling program in 2019 after an extensive needs assessment (Shirley et al., 2021), leveraging seven years of bridge-building experience and relationship development in Rwanda, and nearly two decades of global trailbridge program development. The scale program provided an opportunity to codify and document standard processes and best practices, launch the study described in this paper, and provide new safe access to rural communities on a magnitude unprecedented in Rwanda.

Generally, the identification of potential trailbridge sites involved consultations with residents and officials who were directly affected by the lack of safe water crossings. This multi-stakeholder engagement is a key enabler during bridge construction and monitoring. B2P identified over 1000 potential sites for trailbridge construction in Rwanda, of which 280 in 23 districts were deemed to be technically feasible using B2P's standard designs (Fig. 1). The number of bridge sites in each district ranges from 2 to 35, and the total number of bridges covered in our study is 147, representing 97 intervention and 50 long-term control sites. The construction of the bridges began in 2020 with a randomized build order within each district.

1.3.2. Intervention implementation process and status

Senior B2P engineers reviewed the technical data from all selected sites to identify those that were technically feasible according to B2P's current design standards. This process excluded a large number of sites for which a simple, short span trailbridge is the most efficient solution, and a smaller number of sites that would have required very large-span trailbridges that fall outside of B2P's standards on the basis of cost-effectiveness. Technically feasible bridges were randomized as described earlier in the text. Sites were not excluded on the basis of estimated social impact.

B2P partnerships and operations staff in Rwanda worked with government partners to ensure understanding of the randomization process and adhere as closely as possible to the randomized construction order, sometimes at the expense of operational efficiency and government priorities. Prior to the start of each new fiscal year in Rwanda, B2P staff work with government officials in each district to determine how many trailbridges will be built in each district and the proportion of direct costs to be covered by each party; in Rwanda, the proportion of trailbridge costs covered by government is typically 40 %. Contracts are completed for each project, and B2P operations staff create an annual construction schedule based on the number of projects with funding allocation in each district and the build order assigned to each project as part of the randomization process. Design and construction, including procurement, quality assurance, financial management, and community mobilization, are carried out by B2P staff, though paid and volunteer unskilled labor is provided by community members, and in some cases, a portion of project materials are procured directly by district government partners. Upon project completion and following an official handover, each project is owned by the government of Rwanda. District governments are responsible for maintenance, though B2P provides training for community members and district staff as well as support in the form of technical assistance as needed.

To date, B2P has completed 37 trailbridges at planned intervention sites, with 6 under construction, and 22 sites designated to be long-term controls, based on technical infeasibility after a more thorough technical review. While the launch of the study and the scale program coincided with the onset of the COVID-19 pandemic and forced a reduction in the initial number of projects planned for the period of study, B2P is currently on track to complete intervention projects according to the schedule laid out in this study.

2. Design

Here, we make contributions to mixed methods approaches research by describing how we are combining a stepped-wedge randomized control design with non-experimental methods that include timeseries rainfall analysis and hydrological modeling driven by *in-situ* and remote sensing observations, and statistical modeling. All the trailbridges in this study are being constructed by B2P in 22 districts in western Rwanda. The mixed methods approach will enable estimation of the effects of these bridges on agricultural, educational, health and economic outcomes. We expand on the pilot study by Thomas et al. (2021) by increasing the study sample, duration of observation, and indicators and by introducing methods that help explain causal factors and impacts beyond the intervention sites. Although the presumed positive impacts of infrastructure drive major policy initiatives, studying the effects of infrastructure has been

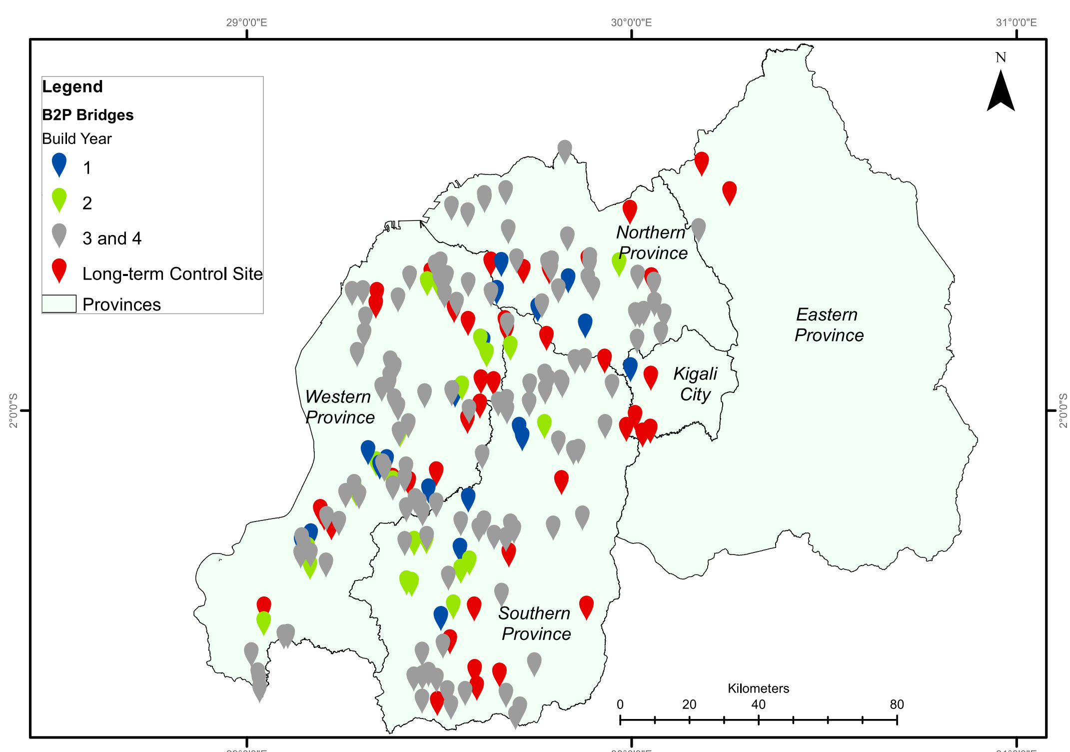

Fig. 1. The map of the study sites. The trailbridges are spread across the Northern, Western and Southern Provinces.

limited by a reliance on pre-existing data that are not well targeted to outcomes of interest (Brooks and Donovan, 2020). This study presents a valuable opportunity to generate and evaluate new data specifically focused on the impact of rural infrastructure.

2.1. Study setting

Rwanda is one of the most densely populated countries in Africa with approximately 500 people per square kilometer and the majority living in rural areas that rely heavily on non-motorized means of transport (Shirley et al., 2021). Our impact evaluation is located in three regions, namely the Northern, Western and Southern provinces (Fig. 1). These regions are characterized by mountainous terrain coupled with multiple rainy seasons that makes it challenging for people to access services outside of their localities (Shirley et al., 2021). Poverty rates in the three provinces remain high despite significant progress made by the country in reducing extreme poverty and inequality (McKay and Verpoorten, 2016). Rural transport infrastructure is not well developed, and during extreme rainfall events, makeshift bridges that dominate rural areas in these provinces are unsafe for crossing flooded rivers.

2.2. Conceptual framework and theory of change

Bridge-use and the associated impacts represent a complex theoretical construct that may be challenging to assess. However, using a conceptual model and a theory of change, it is possible for us to define and illustrate a comprehensive assessment of the expected impacts. In Fig. 2, we outline the various components underlying our evaluation study. We identify extreme rainfall events that cause flooding to be a risk to all communities. We then identify two pathways for these communities: those with bridges (intervention sites) and those without (control sites). It is expected that the immediate impacts following flood events will differ between communities in the intervention and control sites. Those with bridges are guaranteed all-year, safe river crossing, providing a critical transportation service that would result in positive outcomes. Some of these outcomes are the target of our evaluation study, including short-term such as reduced flood risks and reduced travel time, and long-term such as improved agricultural productivity.

Communities in the intervention sites are expected to become more resilient as the risk from floods is reduced and all year round access to services is guaranteed by the trailbridges. On the other hand, communities in the control sites face an immediate impact when rivers flood. These impacts may include extended periods of isolation from services available in other communities and urban centres and, in extreme cases, loss of lives. Flood events can last several days, and river water depth can take even longer to subside. Ultimately, communities in the control sites face the risk of losing jobs and income as well as high transportation costs. These short-term outcomes, when unattended, could worsen household poverty and increase vulnerability to future climate impacts.

2.3. Research objectives

Our study design enables us to measure short and mid-term effects based on the data collected and the outcomes of interest. The main study objective is to evaluate the economic, health, agricultural and educational impacts of the B2P trailbridges on nearby and distant households and communities. We will evaluate these impacts in comparison to matched non-intervention communities.

Our evaluation seeks to develop evidence to support the following policy questions:

i. Question 1: Do trailbridges targeted at reducing rural isolation lead to economic, livelihood, health and educational benefits?

We hypothesize that the B2P trailbridges will lead to the reduction of rural isolation, reduction of flood risks and increased participation of people in the intervention villages in activities that improve human wellbeing indicators.

ii. Question 2: What mechanisms and intermediate outcomes from these trailbridges lead to impacts?

We hypothesize that the B2P trailbridges lead to positive effects on key indicators including increased labor income and access to health services,

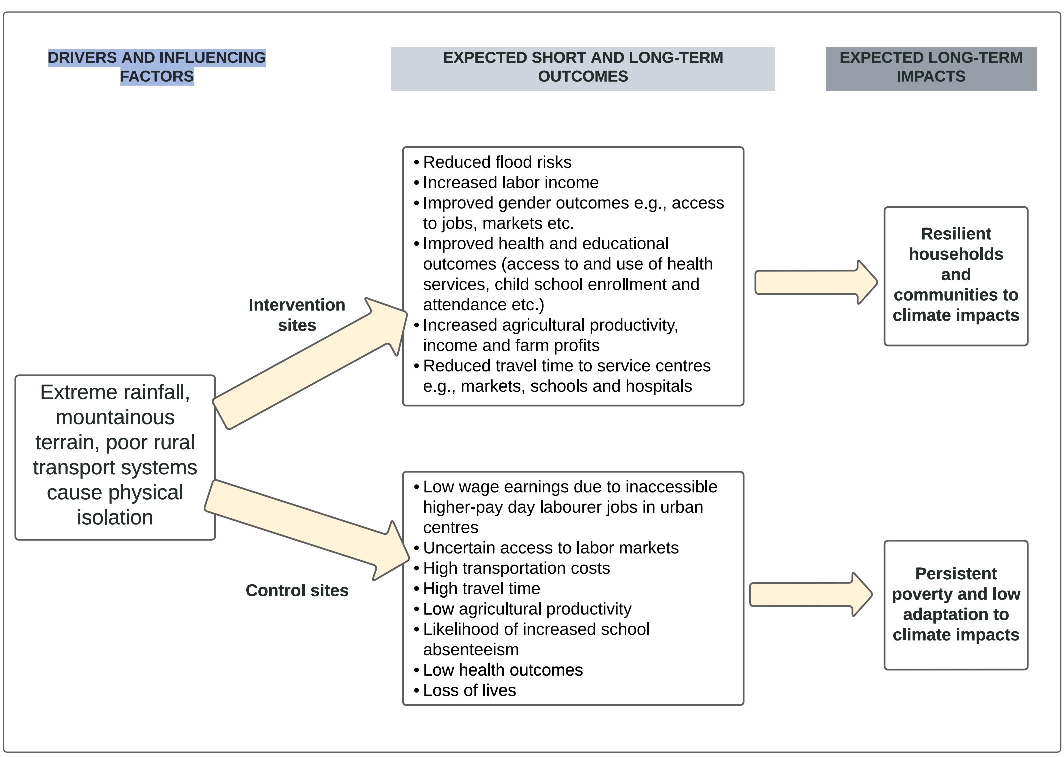

Fig. 2. The conceptual framework and theory of change underpinning this study.

lower transportation costs (time and money), and higher agricultural productivity and income for people in the intervention villages.

iii. Question 3: What set of cost-effective measures and outcomes can be applied to this intervention and others to support an outcomes-based funding model?

This study will generate insights into the impacts of trailbridges and specific outcomes that are impacted most by this intervention. Those insights can then be used to identify mechanisms that can be optimized to scale up such interventions to other communities while targeting outcomes that provide the most returns or benefits.

In addition to the above questions, the sub-studies seek to answer the following questions:

i. Sub-study question 1: Are there significant effects of the trailbridge intervention among households that are more distant from the river crossings?

Earlier results from a set of bridges that are not part of this study showed evidence of trailbridge use by people from villages more distant to the river crossings. There is also evidence that the most significant impacts of new infrastructure are realized by communities that are in close proximity and diminish for more distant communities (Hine et al., 2016). To investigate the extent and magnitude of the impacts of the trailbridges, we hypothesize that the impacts are most significant in the villages at close proximity to the bridges (villages on average 2.5 km from a river crossing) and decrease considerably for more distant villages.

ii. Sub-study question 2: Is there a correlation between weather events, river flow/discharge and bridge use?

Rural mobility can be affected by various biophysical and geographical factors. We hypothesize that there is increased use of the trailbridges during periods of high rainfall and river flows.

iii. Sub-study question 3: What is the impact of the trailbridge intervention on market prices?

Rural transportation infrastructure can have positive impacts on agricultural productivity, including lower input costs and increased farm income from reduced transportation costs, as well as offering growers the opportunity to be more selective in their market participation. However, increased production can also alter the demand-supply balance and create lower farm earnings due to reduced demand. We are following the prices of crops, livestock and agricultural inputs in key market sites to determine the effect of trailbridges on these key variables of agricultural productivity. We hypothesize that the bridges will increase the price of market commodities, beneficial to small holder farmers.

3. Study components

Our impact evaluation design is anchored on a randomized controlled trial (RCT) study supported by three sub studies: 1) distant village study, 2) market study, and 3) hydrological and geospatial modeling study. These study components are illustrated in Fig. 3.

3.1. The randomized controlled trial study design

We are using a stepped-wedge block randomized design (Hemming et al., 2015) for the scale-up study motivated by the pilot study done by Thomas et al. (2021). The steps in the wedge design are yearly. In total, we are following 147 sites over four years (July 2020 to June 2024), for a total sample of 588 site-surveys. Of these, 17 will be built in the first year, 35 in the second and 45 in the third. The remaining 50 sites will not receive a bridge during the study period. Data collection at these sites includes household-level surveys, sensor-based monitoring of bridge use and administrative data collection. Household-level surveys will be conducted at each site once a year for a total of four rounds (one baseline survey and three follow up surveys).

Randomization of trailbridge building was done on the district level to control for any district-level differences. Randomization increases internal study validity (Hargreaves et al., 2016). Threats would arise if randomization failed due to construction or bureaucratic delays significantly disrupting the timing, especially if delays were correlated with observable or unobservable village baseline characteristics. It is possible to test the former while the latter is impossible. For example, tests can be done to ascertain whether or not attrition is correlated with observable village characteristics. Consequently, controls can then be included to limit the impact on estimated treatment effect. This is not possible with unobservable characteristics. In this case, intent-to-treat regressions provide a lower bound on the total impact of the intervention. We expect total attrition to be small, and we have worked to minimize the risk of delays. B2P signed an agreement with the Government of Rwanda, and the construction schedules were planned significantly in advance.

At each bridge site, six members of the research team completed the process of determining which three villages would be most impacted by the completion of the bridge and, therefore, would be the villages in which household surveying was conducted. This process consisted of contacting the cell leaders for the two cells adjacent to the bridge site, on either side of the river. Cell leaders were asked which three villages would be most impacted, according to the criterion that the bridge site was the only route from the village to any of the following: primary school, secondary school, clinic or health center, hospital, market attended by village members at least weekly for some part of the year, significant local employer or labor opportunities, and/or road or transportation connection point to the nearest city or large town. If there was disagreement among the cell leaders and all the suggested villages met at least one of the conditions above, the three suggested villages that were closest to the bridge site were selected for household surveying. The number of surveys per village was determined through the minimum detectable effects (MDE) calculations shown in Table 1, which shows MDE calculations for an estimation strategy employing two-way fixed effects (TWFE) and simulated MDE calculations for the Roth and Sant'Anna (2021) simple average treatment effects estimation procedure (RS).

We have developed a pre-analysis plan for the RCT data. We begin with details on specification. First, randomization was done within districts *via* a computer program. We therefore include district fixed effects in all specifications. Second, we note that the randomization was done without any previous data collection from households within study villages, other than approximate population size. Thus, it is possible that our realized randomization leads to unbalanced features. We will include baseline controls to account for this. Third, and finally, the usual two-way fixed effect specification of the form[1]

$$y_{iv} = \alpha + \beta T_v t + \gamma_v + \theta_t + \varepsilon_{iv} t \tag{1}$$

is problematic in our setting if we expect variation in treatment effects over time. This would happen, for example, if a treated village sees its treatment effect grow or fade in periods-since-treatment. In this case, the time-invariant treatment effect $\widehat{\beta}$ in part uses previously-treated units as "controls" for units treated later, and may induce negative weights on earlier-treated effects (Goodman-Bacon, 2021).

We will instead make use of the procedures detailed in Roth and Sant'Anna (2021), which exploits the randomized treatment timing to deliver more efficient estimates relative to a reliance on (only) a parallel trends assumption.

The main outcomes that we will study are household income and farm productivity, health outcomes, and educational attainment and attendance. In pursuit of the mechanisms behind observed changes, we will study the following secondary outcomes:

- Farm outcomes: Farm outputs (harvest size, crop choice), inputs (fertilizer expenditures, labor), and land use (in- and out-rentals, acreage planted)
- Off-farm outcomes: earnings, the location of those earnings, wages

[1] Subscripts ***i***, ***v***, and ***t*** denote household, village, and year, respectively. $T_{vt} = 1$ when village v is treated at year t and 0 otherwise.

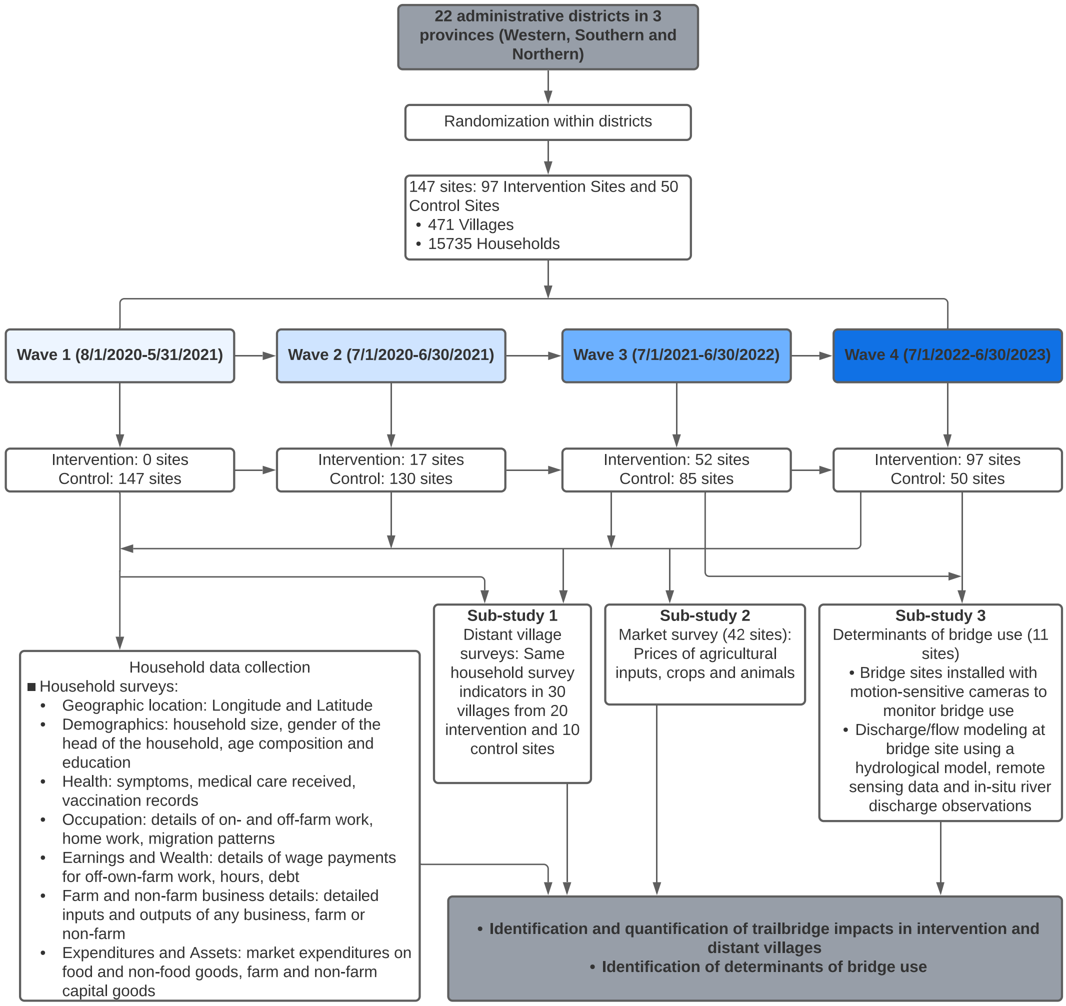

Fig. 3. Flowchart illustrating the key components of the impact evaluation study.

- Connection to market: sales of crops in market, expenditure patterns on non-crop consumption in the market

We will also study heterogeneity in these effects. The main interactions will include

- Household-level: savings, wealth
- Village-level: distance, indicator for whether the village is on the side of the bridge closer to market, market prices for main consumption goods

The latter will be carried out in the subset of households for which data exists (which is relevant for the "distant" villages and market-level mediating variables).

Table 1
Minimum Detectable Effects selected for the RCT study. SD and ICC are the standard deviation and the intraclass correlation coefficient, respectively.

Outcome	Mean	SD	ICC	MDE (TWFE)	MDE (RS)
Household food expenditure	5596.92	7.081.74	0.09	275.70	508.25
Household total labor earnings	1051.67	3411.01	0.01	129.71	109.13
Use of fertilizer	0.58	0.49	0.21	0.20	0.03
Spending on fertilizer	7118.37	20,122.37	0.10	779.90	1489.88
Likelihood to work outside community	0.58	0.49	0.10	0.02	0.02
Visited clinic in the last month	0.32	0.47	0.03	0.02	0.02
Mid-upper arm circumference	15.26	2.12	0.05	0.08	0.11

3.2. Distant villages

The distant villages study is motivated by results from an earlier assessment of bridges constructed in Rwanda but which are not part of our study. A catchment assessment program launched in 2019 by B2P found that the bridges served a geographic area that was larger than initially estimated pre-construction. It was found that the bridges served 11 times the number of villages determined in the preliminary assessments (Bridges to Prosperity, 2020). We have established 30 distant villages that we are following, conducting the same household-level survey intended to investigate the extent of impacts by the bridges in the scale-up study. Specifically, at 20 intervention sites and 10 long-term control sites, ten additional household-level surveys were conducted in distant villages. A distant village was defined as one whose boundary is 2.5 km from the bridge site, not within 2.5 km from another completed or anticipated bridge site, and adjacent to a national or district road. Where multiple villages met that criteria at a single site, one was randomly selected. These surveys will support the development of a statistical model examining the impact of the trailbridges among communities at varying distances from the bridge sites.

3.3. Market price surveys

Market price data collection began in April 2021 at 22 sites. At each site, a set of criteria were used to identify nearby markets that would be potentially impacted by the construction of a trailbridge at that site. A list of potential markets was drawn through consultation with village leaders. Three village leaders at each site were interviewed and the markets with the most mentions were selected for this study. Key indicators for identifying potential markets included location, means of travel from the village to the market, markets where most of the community members commonly buy food, and the type of crops sold and purchased from the market. If the market was the same as where people buy and sell agricultural inputs (seeds and fertilizer), the village leaders were asked about the next most important market. In total, 42 markets were identified for these sites. At each market, the following data collection was carried out: (1) an initial round of vendor surveys by enumerators with 5–15 vendors per market, depending on market size; and (2) shorter monthly vendor surveys by local enumerators to monitor market prices. In April 2022, data collection will begin at impacted markets for an additional 22 sites.

3.4. Determinants of bridge use

Extreme weather events influence demographic behavior (Carrico et al., 2020). People are likely to choose to use the trailbridges during high rainfall and river flows when alternative river crossings are risky to use. To investigate this relationship, we are using multi-year high spatial resolution and bias corrected gridded satellite rainfall data to determine trends in extreme rainfall events in the study sites. The choice to use these data was made due to lack of quality and adequate rain gauge data that are spatially detailed to enable analysis at the scale of a bridge catchment. We will evaluate four rainfall indices: annual precipitation total in wet days, annual total precipitation when rainfall >95*th* percentile of a baseline period, annual count of days when rainfall is ≥10 mm and ≥ 20 mm, and monthly maximum consecutive 5-day precipitation. These indices will enable us to determine long-term trends in rainfall amounts that cause flooding, and to correlate rainfall events with bridge use data. We will then use a hydrologic model combined with the timeseries rainfall data and other remote sensing data to simulate river flow at each bridge site at the daily timescale. We will use the Variable Infiltration Capacity model (VIC), which is a distributed macroscale hydrologic model that has been widely used in streamflow simulations globally, including East Africa (Liang et al., 1994; Shukla et al., 2014, 2015; McNally et al., 2017). The VIC model will be calibrated over the study domain shown in Fig. 4.

Motion-activated cameras have been installed at eleven bridge sites. These cameras record short videos and still photographs of objects crossing the bridges at short intervals. The cameras are enabled with infrared sensors in order to also track bridge use at night. A prior pilot by Thomas et al. (2020) connected four bridge sites with cameras and developed a computer vision supported algorithm for counting bridge crossings with very high correlations when compared with manual counting. This research will integrate data from the cameras with rainfall data, river discharge, other geographical covariates from the household surveys, and geospatial analysis to estimate a set of models that explain the relationship between bridge use and social-environmental conditions. The proposed analytical framework is shown in Fig. 5. Using this framework, we will also use statistical and geospatial approaches to investigate whether there are significant differences between outcomes measured through the RCT study in the intervention and control sites, with and without the bridge use data.

4. Preliminary results from the baseline study

4.1. Baseline summary

Baseline surveys were carried out between the beginning of August 2020 and the end of May 2021 in all 147 sites. At each site, 105 surveys were done, representing 35 household surveys in three villages. Additional surveys at more distant villages were carried out at 30 of the study sites. Generally, the survey modules include:

i. Geographic location of the household in longitude and latitude dimensions

ii. Demographics: household size, gender of the head of the household, age composition and education

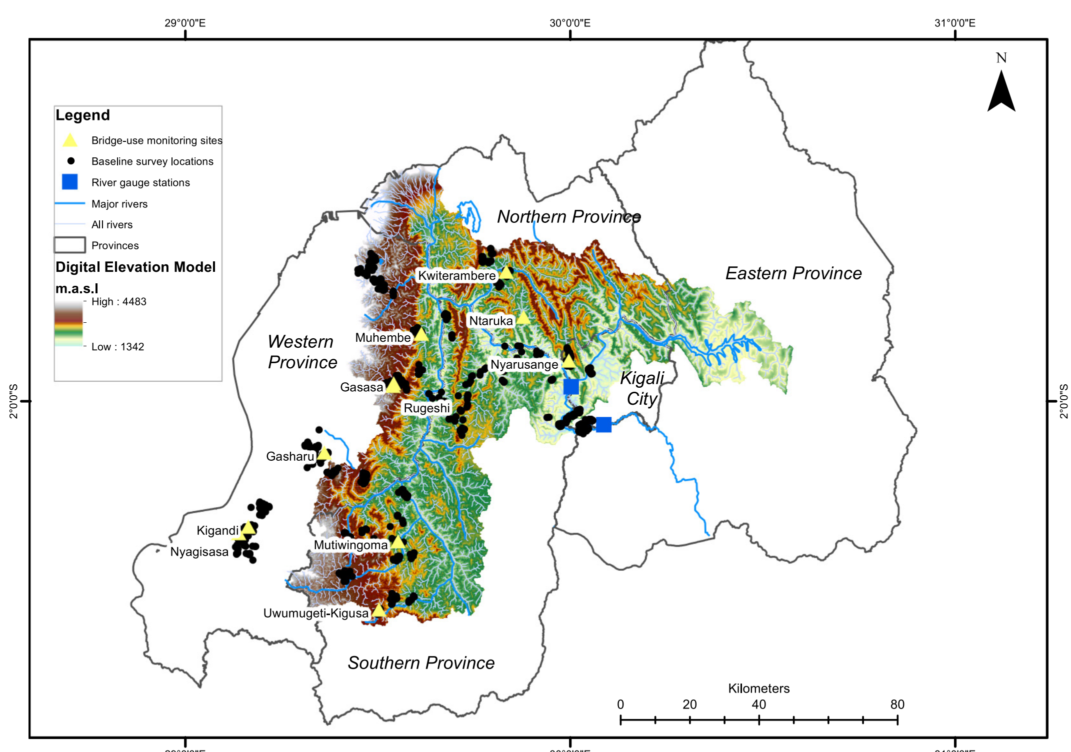

Fig. 4. Map showing the catchment domain where discharge modeling will be conducted. The Variable Infiltration Capacity (VIC) model will used to estimate river discharge in eight out of the eleven bridge sites (yellow triangles) where motion cameras have been installed to monitor bridge use. Blue squares indicate existing *in-situ* river gauging stations that will be used for model calibration and validation. Black circles are locations where household surveys are being carried out across the entire bridge catchment area.

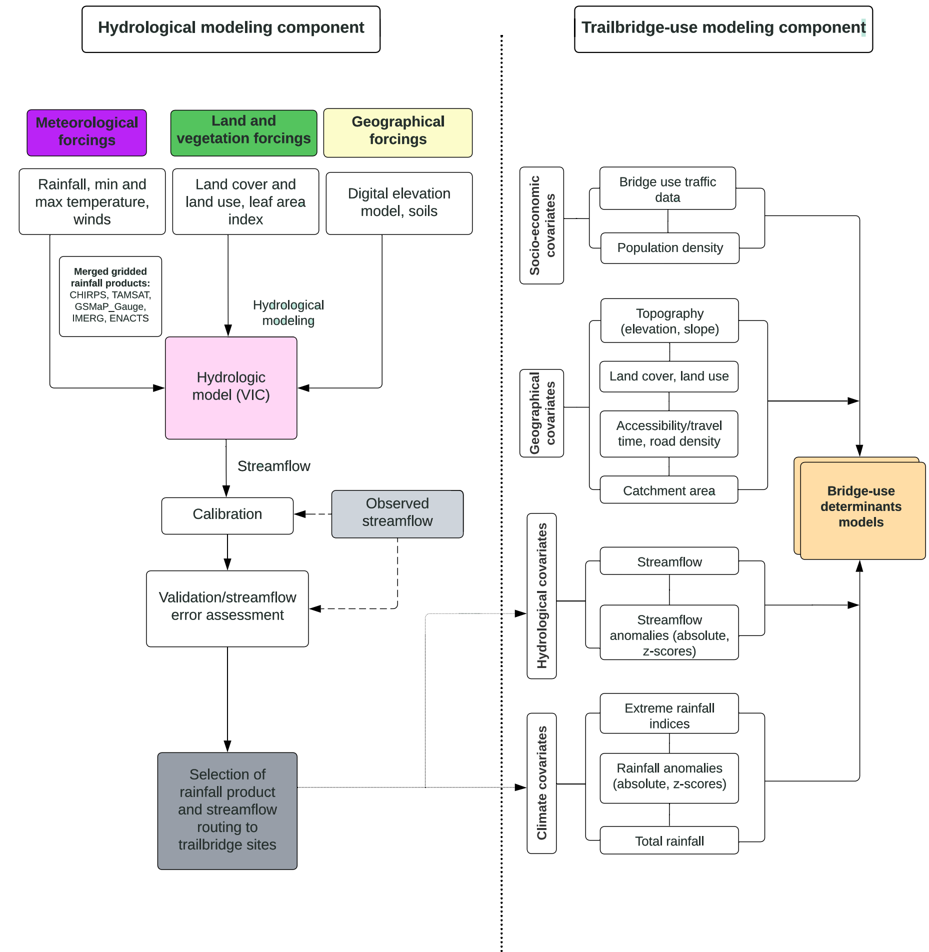

Fig. 5. An illustration of the proposed analytical framework for investigating the determinants of bridge use in the study sites.

iii. Health: symptoms, medical care received, vaccination records

iv. Occupation: details of on- and off-farm work, home work, migration patterns

v. Earnings and Wealth: details of wage payments for off-own-farm work, hours, debt

vi. Farm and non-farm business details: detailed inputs and outputs of any farm or non-farm business

vii. Expenditures and Assets: market expenditures on food and non-food goods, farm and non-farm capital goods

4.2. Household characteristics

In the baseline, 15,852 total households and 73,071 total household members were surveyed. The gender proportions of the surveyed household members were 46.9 % male and 53.1 % female. The median number of household members was 4 whereas the median age of household members was 18 years, with 60.9 % of household members being <25 years old.

4.3. Roles and activities

Of the households, 97.7 % had at least one member that took care of the household, 93.4 % had at least one member who reported working on their own farm, 72.0 % had at least one member who reported attending school, 70.0 % had at least one member being paid to work for someone else and 11.4 % had at least one person who operated their own non-farm business. While larger fractions of women reported taking care of households and work on the farm as compared to their male counterparts, larger fractions of men reported attending school, being paid to work for someone else and operating their own non-farm business.

4.4. Income sources

4.4.1. Jobs

Job in the survey is defined as any activity where household members were paid for their work that does not include working on their own farm or business. Of household members between the ages of 16 and 65, 53.2 % were paid to work for someone else. Of those, 30.7 % had their primary jobs inside their communities while 42 % worked outside of their communities. Of those working outside their communities, 63.3 % reported working in agriculture, while 17.3 % reported occasional labor, and 5.4 % reported construction. Similarly, of household members that worked inside their communities, 71.1 % reported working in agriculture, while 13.9 % reported occasional labor, and 4.5 % worked in construction.

The median earnings for construction jobs were higher for workers whose jobs were outside of their communities as compared to those that worked within their communities. Agriculture and occasional labor earnings were the same for the two locations (Table 2).

4.4.2. Crop cultivation, animal rearing and food consumption

Out of all the households included in the baseline, 96.3 % reported cultivating crops. Crops that were grown by at least 5 % of the households

Table 2
Median weekly payments in Rwandan Franc (RWF) household members received for their primary jobs in agriculture, construction, and occasional labor working inside and outside their communities.

Type of Job	Median Weekly Earnings (inside community)	Median Weekly Earnings (outside of community)	Overall Median Weekly Earnings
Agriculture	3500	3500	3500
Construction	7500	10,000	9000
Occasional labor	5000	5000	5000

were beans, sweet potatoes, cassava, maize, bananas, dodo (amaranth), matoke and taro. The most sold crops were bananas, coffee, maize, beans and cassava (Table 3). In addition, 66.2 % of households reported to own animals with cattle, hens, goats, and pigs being the most owned farm animals. Of the owned animals, 11.7 % were sold in the 6 months preceding the baseline survey. The median amount of land used for cultivating crops was 1780 square meters. Out of the households that cultivate crops, 70.8 % purchase seeds, 61 % purchase fertilizers and 29.5 % purchase pesticides. A small proportion of the households (0.1 %) reported that they purchase herbicides.

Apart from income generated from jobs and farming, on average, households reported earning more money from government programs and families located in Rwanda as compared to other income sources listed in the survey, including income from charity organizations and families outside Rwanda.

Food consumption was dominated by vegetables, salt, beans, sweet potatoes, cooking oil and cassava flour. The six commodities were consumed by >50 % of the households (Fig. 6). Most of the spending reported by these households goes to food representing about 72.7 % of the total spending.

4.5. Travel across rivers

From the surveys, 57.4 % of the households reported having to cross rivers to reach a hospital, 61.2 % to reach banks, 30.1 % to reach government offices, and 56.9 % to reach markets where they purchase most of their food. Of the 96.3 % of households that reported cultivating crops, 25.8 % cross rivers to get to their farmlands. Of the households that reported crop cultivation, 32.5 % reported taking the crops to outside markets to sell them. Of the 32.5 %, 68.7 % reported crossing rivers to get to the markets where they most commonly sell their produce. Additionally, 30.1 % of households have at least one member who crosses the river to reach their school and 37.3 % of households have at least one member who crosses the river to reach their first (primary) job.

A majority of households (78.3 %) spend 30 min or less traveling to farms (Table 4). It takes >40 % of households >30 min to reach a hospital and more than a quarter of these households spend more than one hour to access a hospital. In addition, a majority (69.4 %) travel between 30 min and two hours to access a financial institution. Close to half of the households reported spending >30 min to access a government office.

Table 3
Table showing the fraction of households that grow and sell crops, and the sell-grow ratio.

Crops	Fraction of households that grow	Fraction of households that sell	Sell/Grow ratio
Beans	0:84	0:09	0:11
Sweet potatoes	0:68	0:05	0:07
Maize	0:60	0:10	0:17
Cassava	0:60	0:07	0:12
Bananas	0:47	0:22	0:47
Irish potatoes	0:19	0:06	0:32
Coffee	0:13	0:10	0:77

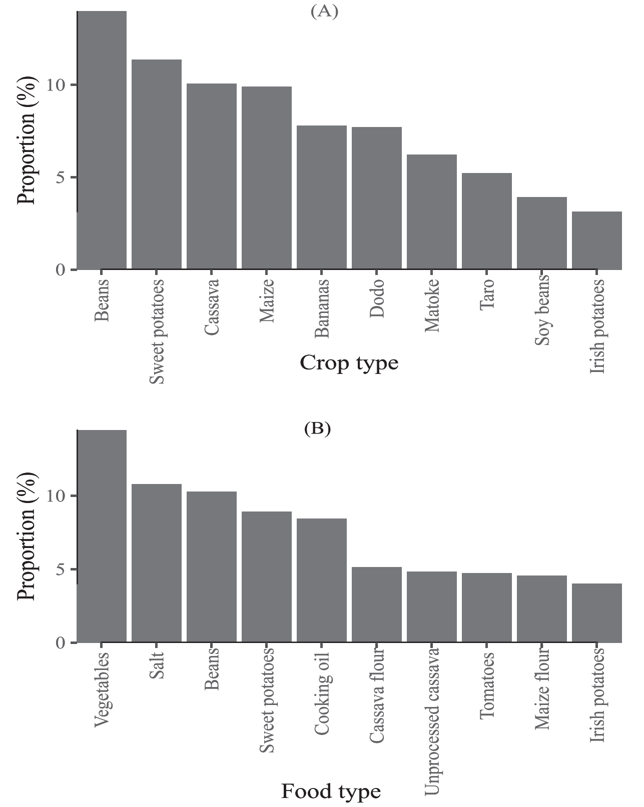

Fig. 6. Percentage of the top ten crops grown (A) and food purchased (B) out of all crops and food purchased by the households, respectively.

In addition, 19.2 % of the households reported spending 30 min or less traveling to school whereas 10.1 % spent between 30 min and one hour getting to school. On the other hand, 10.6 % of the households reported spending 30 min or less traveling to work while about 6.1 % spent between 30 min and one hour getting to work.

4.6. Health and food security

Of all household survey respondents, 25 % reported experiencing headaches in the past month, while 22 % reported joint pain, and 14 % reported coughs. While 23 % of respondents received medical care for “other” symptoms, 15 % received care for headaches and 10 % received care for joint pain. Of the 23 % that received care for other symptoms, >40 % stated Malaria as the health problem followed by toothache and stomachache. Of all households, 20 % reported that at least one household member is 5 years old or younger and has experienced a runny nose in the past month. Similarly, 21 % reported coughs, while 73 % reported none of the symptoms.

Table 4
Percentage of households that reported the travel times (in minutes) it would take for them to reach each of the destinations. The NA category is for the percentage of households that were not asked the relevant travel time questions (3.67 % of households do not cultivate crops and 68:7 % do not take their crops to outside markets to sell them). The bold values show the mode travel times for each destination.

Travel time (min)	Farmland	Hospital	Market (for selling)	Market (for purchasing)	Bank	Government Office
NA	3:67	0:00	68:74	0:00	0:00	0:00
0–30	**78.31**	25:46	6:42	**36.44**	15:39	**49.33**
361–120	13:34	**40.29**	**11.06**	31:60	34:68	38:10
61–120	3:44	26:56	9:62	23:58	**34.71**	10:24
121–180	0:53	5:33	3:12	6:36	11:06	1:02
Other	0:72	2:36	1:03	2:02	4:16	1:31

>50 % of respondents reported eating a limited variety of food, eating fewer meals a day, eating foods that they did not want, being unable to eat preferred food, and worrying that their family will not have enough food often (>10 times) in the past four weeks. However, >50 % of households rarely went a whole day and night without eating.

5. Discussion

This implementation research aligns with existing policy priorities within Rwanda. The country's National Strategy for Transformation launched in 2017 is a 7-year plan that focuses on meeting the Sustainable Development Goals (SDGs) through economic, social and governance transformation. Toward this end, the Ministries of Infrastructure, Local Government, and Finance and Economic Planning have partnered with B2P to serve one million Rwandese with >200 trailbridges over a 5-year period. The evidence generated from this research will be used to inform the strategy and other infrastructure-related efforts, as well as by B2P to increase the evidence base for rural infrastructure programs in new geographies. The study will advance knowledge by generating new data on the impact of rural infrastructure and providing the opportunity to explore a range of outcomes for future evaluation of infrastructure in low- and middle-income countries. We will enable an outcomes-based funding model that ties implementer payments to demonstrated positive impacts of these trailbridges. Furthermore, we will identify cost effective, easily assessed measures that are highly correlated to the economic and health benefits of the intervention. These measures will include electronic counting of bridge crossings, correlated to village level impacts. These measures may then be used by a portfolio of interventions across multiple geographies without always requiring complex trials.

Household consumption is a particular outcome of interest. It is most often measured through surveys and frequently relied upon by investigators when trying to measure living standards and poverty in low- and middle-income countries. In spite of the utility of consumption for such efforts, the different methods for measuring consumption, which are applied in different contexts, with different populations, over different time periods, makes it challenging to compare the results between studies and to track changes over time. Our study proposes to construct a transferable measure of household consumption derived from a consistent methodology for potential application across varying types and locations of interventions.

This evaluation will also generate evidence to enable decision making by national level governments on policy and investment in support of rural transportation infrastructure. Although the presumed positive impacts of infrastructure drive major policy initiatives, studying the effects of infrastructure has been limited by a reliance on pre-existing data that are not well targeted to outcomes of interest. The proposed research effort presents a valuable opportunity to generate and evaluate new data specifically focused on the impact of rural infrastructure.

CRediT authorship contribution statement

Conceptualization: D.M., L.M., L.M., K.D., W.B., A.N., C.B., K.D. and E.T.; Data curation: D.M., L.M., L.M., K.D., W.B. and S.G.; Formal analysis: D.M., L.M., K.D., W.B., S.G. and E.T.; Funding acquisition: L.M., K.D., W.B. and E.T.; Investigation: D.M., L.M., L.M., K.D., W.B., S.G., A.N., C.B., K.D. and E.T.; Methodology: D.M., L.M., L.M., K.D., W.B., S.G., A.N., C.B., K.D. and E.T.; Project administration: L.M., L.M. and E.T.; Writing – original draft: D.M., L.M., L.M., K.D., W.B., S.G., A.N., C.B., K.D. and E.T.

Ethics board approvals

This study was approved by the Rwanda National Ethics Committee (128/RNEC/2021) and the University of Colorado Boulder Institutional Review Board (20–0087).

Funding

This study was funded by the United States Agency for International Development Development Innovation Ventures under the terms of award number 7200AA20FA00021, the Autodesk Foundation and the Wellspring Foundation.

Declaration of competing interest

We declare the following interests: Co-authors Christina Barstow and Abbie Noriega are staff of the non-profit organization, Bridges to Prosperity, and are in-charge of overseeing the construction of bridges in Rwanda.

Acknowledgments

We thank all of the participants who are involved in this study including fieldwork staff in Rwanda and the support from the Government of Rwanda.

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